

AD-A058 485

AERONAUTICAL RESEARCH LABS MELBOURNE (AUSTRALIA)
CRACK DEPTH MEASUREMENT BY ULTRASONICS.(U)
DEC 77 P A DOYLE, C M SCALA
ARL/MAT.107

F/G 20/11

UNCLASSIFIED

1 OF 1

AD
A058 485



NL



END
DATE
FILMED
11-78
DDC

ADA 058485



B.S. 12

DEPARTMENT OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION
AERONAUTICAL RESEARCH LABORATORIES
 MELBOURNE, VICTORIA

MATERIALS REPORT 107

CRACK DEPTH MEASUREMENT BY ULTRASONICS

P. A. DOYLE and C. M. SCALA

AD No. _____
 DDC FILE COPY

DDC
RECEIVED
 SEP 8 1978
REGISTERED
 E

Approved for Public Release.



© COMMONWEALTH OF AUSTRALIA 1977

COPY No 18

38 08 29 002

DECEMBER 1977

THE UNITED STATES NATIONAL
TECHNICAL INFORMATION SERVICE
IS AUTHORIZED TO
REPRODUCE AND SELL THIS REPORT

APPROVED
FOR PUBLIC RELEASE

DEPARTMENT OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION
AERONAUTICAL RESEARCH LABORATORIES

⑥ CRACK DEPTH MEASUREMENT BY ULTRASONICS
⑨ MATERIALS REPORT, 107
by
⑩ P. A. DOYLE and C. M. SCALA

SUMMARY

A review is given of both bulk and surface wave ultrasonic methods for the measurement of the depth of surface-breaking cracks. Research is considered which relates to techniques for measuring crack depth by studying the scattered pulse amplitude, by using time-of-flight methods, or by carrying out ultrasonic spectroscopic analysis. Measurement of the transit time of bulk waves appears most likely to provide simple and reliable depth measurement in the near future, although further work in the other two areas should lead to the development of valuable techniques. Some suggestions are made of promising directions for future research.

⑭ ARL/MAT. 107

⑪ Dec 77

⑫ 23p

POSTAL ADDRESS: Chief Superintendent, Aeronautical Research Laboratories,
Box 4331, P.O., Melbourne, Victoria, 3001, Australia.

28 08 29 002

008 650

DOCUMENT CONTROL DATA SHEET

Security classification of this page: Unclassified

- | | |
|---|---|
| <p>1. Document Numbers:</p> <p>(a) AR Number:
AR-000-1107</p> <p>(b) Document Series and Number:
Materials Report 107</p> <p>(c) Report Number:
ARL-Mat.-Report-107</p> | <p>2. Security Classification:</p> <p>(a) Complete document:
Unclassified</p> <p>(b) Title in isolation:
Unclassified</p> <p>(c) Summary in isolation:
Unclassified</p> |
|---|---|

3. Title: CRACK DEPTH MEASUREMENT BY ULTRASONICS

- | | |
|---|---|
| <p>4. Personal Author(s):
P. A. Doyle and
C. M. Scala</p> | <p>5. Document Date:
December, 1977</p> |
|---|---|
6. Type of Report and Period Covered:

- | | |
|---|---|
| <p>7. Corporate Author(s):
Aeronautical Research Laboratory</p> | <p>8. Reference Numbers:
(a) Task: DST 76/95
(b) Sponsoring Agency:</p> |
|---|---|

9. Cost Code:
344790

- | | |
|---|--|
| <p>10. Imprint:
Aeronautical Research Laboratories,
Melbourne</p> | <p>11. Computer Program(s)
(Title(s) and language(s)):
—</p> |
|---|--|

12. Release Limitations (of the document): Approved for public release

12-0. Overseas:	No.		P.R.	I	A		B		C		D		E
-----------------	-----	--	------	---	---	--	---	--	---	--	---	--	---

13. Announcement Limitations (of the information on this page): No Limitation

- | | |
|---|--|
| <p>14. Descriptors:</p> <p>Cracks Depth measurement</p> <p>Ultrasonic tests Non-destructive tests</p> | <p>15. Cosati Codes:</p> <p>1113</p> <p>1402</p> |
|---|--|

16.

ABSTRACT

A review is given of both bulk and surface wave ultrasonic methods for the measurement of the depth of surface-breaking cracks. Research is considered which relates to techniques for measuring crack depth by studying the scattered pulse amplitude, by using time-of-flight methods, or by carrying out ultrasonic spectroscopic analysis. Measurement of the transit time of bulk waves appears most likely to provide simple and reliable depth measurement in the near future, although further work in the other two areas should lead to the development of valuable techniques. Some suggestions are made of promising directions for future research.

B

CONTENTS

	Page No.
1. INTRODUCTION	1
2. SCATTERED AMPLITUDE METHODS	1
2.1 The Pulse-Echo Technique	1
2.2 Depth Measurement from First Principles	2
2.3 Other Amplitude Methods	2
3. TIMING METHODS	
3.1 Bulk Wave Timing Methods	3
3.2 Surface Wave Timing Methods	4
4. ULTRASONIC SPECTROSCOPIC ANALYSIS	5
5. DISCUSSION	6
6. REFERENCES	8
FIGURES	
DISTRIBUTION	

ACCESSION for		
NTS	White Section	<input checked="" type="checkbox"/>
DDC	Buff Section	<input type="checkbox"/>
UNANNOUNCED		<input type="checkbox"/>
JUSTIFICATION.....		
BY.....		
DISTRIBUTION/AVAILABILITY CODES		
Dist.	AVAIL. and/or SPECIAL	
A		

1. INTRODUCTION

Ultrasonic methods are widely used in the detection of both internal and surface defects in structural materials. Because of increasing design complexity, e.g. the application of fracture mechanics concepts to aircraft design¹, there is a special motivation to develop quantitative, rather than qualitative, techniques for non-destructive evaluation (NDE).

This paper reviews recent ultrasonic research directed towards the measurement of the depth of surface-breaking cracks, which have already been located by ultrasonic or other NDE methods. Both bulk (P or S) and surface (R) wave techniques are included. The first general approach considered is the relationship between crack depth and the strength of the signal scattered by a crack from an ultrasonic beam. Next, depth measurement based on the transit times for waves following various paths around the crack is reviewed. Finally, the potential of ultrasonic spectroscopic analysis to measure small cracks and indicate crack morphology is discussed. When it helps clarify the state of the art for surface flaws, brief consideration is given throughout the paper to related work dealing with the ultrasonic examination of internal flaws. The potential of ultrasonic and acousto-optical imaging techniques is not discussed in this review.

2. SCATTERED AMPLITUDE METHODS

2.1 The Pulse-Echo Technique

The most common use of an ultrasonic probe is in the simple pulse-echo technique which detects the return signal scattered by a flaw situated beyond the "dead zone" of the transducer². The strength of the signal gives some indication of the size of the flaw, but quantitative estimation of size requires careful interpretation. One approach to this analysis is to compare the signal with that scattered by a known standard defect. Hitt³ introduced flat-bottomed holes in test blocks made from the same material as the specimen under test as reference standards for scattering by internal defects. While flat-bottomed hole standards are still used, Hislop⁴ argued that the so-called AVG (distance—signal voltage—defect size) diagram of Krautkrämer⁵, which quantifies the flat reflector system without actually needing sets of test blocks, provides a simpler standard for internal flaw measurements.

For the surface cracks of primary interest in this paper, reference standards often consist of spark eroded slots or saw cuts produced in a position geometrically similar to that for the crack to be measured. However, many difficulties are associated with the use of artificial reference defects⁶. Even after transducer coupling variations are avoided, the return signal is influenced by crack shape, crack surface roughness and mode conversion upon reflection. The signal also varies with the frequency, mode and bandwidth of the probe. Further, much of the ultrasonic intensity can be transmitted across an unloaded fatigue crack, causing the return pulse to depend on the state of stress in the region of the crack⁷. For an assembled structure, this state of stress is determined by material type, crack growth history, the amount of stress relaxation, and induced stresses⁸. Finally, the ignoring of interference effects which depend on crack size and orientation, can cause under-estimation of crack depth. These effects prevent the intensity of the reflected pulse from always increasing monotonically with crack depth, as is assumed in simple theory^{9,10}.

Corbly *et al.*⁷ overcame some of the above difficulties by using a known fatigue crack, in the same material and geometrical configuration as the unknown crack, as a reference standard for the pulse-echo technique. They employed S-wave reflection to find the depths of fatigue cracks as small as 0.5 mm to ± 0.2 mm. While this accuracy is excellent, the unknown cracks were prepared by the same constant amplitude loading cycle as the standard crack. Further work is needed to establish if and when the varying loading history of cracks encountered in practice significantly alters their reflectivity, thereby influencing the reliability of this technique.

2.2 Depth Measurement from First Principles

In parallel with the development of empirical methods which rely on reference standards, a more fundamental approach to crack depth measurement is being sought through more detailed consideration of the scattering processes involved. The complexity of the interaction of a beam with a surface flaw has been graphically illustrated by Baborovsky *et al.*¹¹, who used Schlieren visualization to demonstrate the interaction of an S-wave pulse with a slit. They describe fourteen possible main P and S scattered pulses produced by various combinations of mode conversion and diffraction from a single incident pulse. Not all of these scattered pulses are strong for any one crack orientation and incident pulse direction, although a strong return will occur from almost any of them at suitable incident angles. Fig. 1 sketches as an example the field produced by a 2 MHz shear wave pulse incident at 35° on a slit two wavelengths deep in steel. It is possible for the back scattered pulse to disappear altogether at suitable angles and depths, which emphasises the caution needed in applying the pulse-echo technique.

The more fundamental and general approach to depth measurement would be possible by developing exact solutions for the interaction between the beam and the flaw and then determining depth by comparing theory and experiment at suitable scattering angles. A major obstacle to development along these lines is the difficulty of obtaining exact solutions for the scattering of elastic waves; even for scatterers in infinite media, solutions exist for only a few simple geometrical shapes¹³. This difficulty has led to a search for suitable approximate solutions. For the case of internal spheroidal and cylindrical defects, calculations based on the first Born approximation^{14,15} have been compared with experiment by Tittmann¹⁶ who found good agreement for back-scattering from small obstacles. Tittmann¹⁶ and Adler and Lewis¹⁷ used Keller's geometrical theory to approximate the scattering from disc-shaped flaws (which resemble internal cracks), and found good agreement with experiment for the larger scatterers for which Keller's theory is valid.

For surface cracks, multiple scattering due to the proximity of the surface to the obstacle is a further serious complication. Bennett¹⁸ expressed the total field for a set of scatterers due to multiple scattering in terms of the field reflected by each scatterer in isolation. He calculated as an example the field in the neighbourhood of a cylinder adjacent to a plane free surface, which required numerical approximation by steepest descent of some integrals. Extending this work to the case of a crack at a surface would be valuable, though the formulation is complicated. A useful, but less rigorous, approach was adopted by Baborovsky *et al.*¹⁹, who numerically treated each point on the illuminated crack face as a Huygens's source radiating in all directions (Fig. 2). The calculated field at an exit point includes up to eighteen contributions from waves undergoing one to three scattering events, having due regard to mode conversion. Empirical corrections are included for head waves, surface waves and waves generated at the crack tip. These authors found broad agreement between computed scattered fields and Schlieren photographs of the type sketched in Fig. 1. They made a preliminary study of the pulse-echo technique by concentrating on the back-scattered part of the field, and found encouraging agreement between calculated and measured curves of intensity versus defect depth. The value of further work along these lines may depend on the validity of the approximations inherent in the numerical calculations for the near field of the scatterer.

The approach to crack depth measurement from first principles, as discussed here, is providing the necessary understanding of the interaction between ultrasound and defect, which in itself is sufficient motivation for its continued pursuit. It may be however that, for the next few years at least, simpler and more reliable crack depth measurement will be based on other approaches, particularly the timing methods discussed below.

2.3 Other Amplitude Methods

A number of other methods using scattered amplitude to measure crack depth have been proposed. Böttcher *et al.*²⁰ arranged two angle probes on opposite sides of a slit in mild steel (Fig. 3); a signal dependent on slit depth reaches the receiver due to scattering by those grain boundaries beyond the slit edge. Silk and Lidington²¹ pointed out that diffraction by the edge also contributes to the signal. Crack depth could be measured by comparing the signal received from an unknown defect with those from known slits, provided the calibration could be reliably

established. However, there are significant differences between measurements by the two groups of authors, and further work would be needed to improve the calibration. Silk and Lidington indicate a number of disadvantages of this method; these include commonly occurring random errors caused by scattering from inclusions in the steel and by probe coupling variations. Also, the technique is limited to cracks at least 3–4 mm deep, due to the physical size of transducers and probe beam width and to the need to eliminate interfering surface waves. They found that a more accurate and reliable depth measurement can be made with this probe configuration by using a timing technique, as discussed below.

During a study by photoelastic visualization of the interaction of surface waves with slits, Reinhardt and Dally²² noted that the variation of transmission and reflection coefficients with crack depth might provide a basis for the measurement of small cracks less than half a wavelength deep. The transmission of surface waves past a crack in a fatigue test specimen has in fact been used²³ to monitor crack growth from an initial precrack 1.2 mm deep. The reflection coefficient for surface waves, which varies more markedly than the transmission coefficient for cracks much smaller than the wavelength, may prove useful for the measurement of very small cracks; this possibility does not yet seem to have been thoroughly investigated.

Finally, we consider a rather different technique proposed recently by Silk²⁴. When a surface wave is directed towards a crack, part of the energy travels down the crack face and is radiated over a wide range of angles as S-waves from the tip (Fig. 4). An S-wave detector of known angle ϕ should give maximum response at two positions, one on each side of the crack tip. Once these two positions are located (for one surface of the specimen), the crack depth can be readily found geometrically. This technique has the advantage of requiring neither a reference standard nor a detailed study of the scattering process. Silk measured fatigue crack depth greater than 8 mm to an accuracy of 13% with this method, though it is unsuitable for application to small cracks.

3. TIMING METHODS

3.1 Bulk Wave Timing Methods

Di Giacomo *et al.*²⁵ directed an S-wave towards a crack at an angle by reflection from the back face of a plate (Fig. 5), then shifted the probe away from the crack face until the position shown in Fig. 5a was reached, at which the back-scattered pulse was about to disappear. They measured the time lag between generation and reception of the reflected pulse as well as that when the transducer was moved back through the maximum amplitude to the point where the signal was again about to disappear (Fig. 5b). The crack depth was found from these two measurements by eliminating the effective beam divergence from the calculation. The technique gave the depth of tight fatigue cracks in plate specimens within a standard error of 2–3 mm for cracks up to about 30 mm deep.

Di Giacomo *et al.* described an alternative method having similar accuracy which is suitable for deep cracks (≥ 10 mm), in which they replaced one of the measurements by moving the probe close to the crack, and measured the transit time corresponding to disappearance of the direct reflection from the crack tip. A focused beam probe could improve both variations of the technique by giving greater sensitivity for tight cracks and by resolving more abrupt changes in crack edge profile. Although these authors did not discuss the possibility, their methods could be readily modified to provide depth measurement for cracks opening onto inaccessible surfaces. While use was made of signal amplitude to eliminate the finite beam width, the self-normalization implicit in the technique led Di Giacomo *et al.* to find values for depth almost independent of the absolute magnitude of the scattered pulse. Thus this technique provides a bridge between those methods described above which depend on signal amplitude, and those which are solely variations on the time-of-flight approach.

Silk and Lidington²¹ used the configuration of Fig. 3 to determine the depth of artificial slits by measuring the time delay between the transmission of a short longitudinal pulse, and its reception after scattering by the crack edge. With a knowledge of probe separation and wave speed in the specimen, elementary geometry relates crack depth to this time. A shallow angle of 20° for beam entry was required to achieve a scattered pulse height significantly above noise level; this geometry causes a loss in the accuracy of depth measurement proportional to $\sin 20^\circ$.

However, given this sufficiently strong diffracted P-wave, the required pulse was easily identified, since it preceded any other pulses arriving at the receiver, such as mode converted S-waves or possibly surface waves. Slots 10–40 mm deep were measured to an accuracy of ± 0.5 mm. Silk and Lidington²⁶ later used this technique, making meaningful time measurements as short as 20 ns, to measure the depth of artificial slits 1–30 mm deep to within ± 0.25 mm. For slits of varying depth, they measured the profile of the edge. A very shallow beam entry angle of 10° was necessary for the smaller slits, in order to maximize the diffracted pulse by causing the centre of the beam to impinge more nearly on the edge of the crack.

Recently actual fatigue crack depths in steel have been measured²⁷ to ± 0.2 mm using 2.5 MHz longitudinal probes, though in all cases reported the cracks were at least 6 mm deep. Since the measured depth is a weighted average over the beam spread along the crack edge, less accuracy is obtainable near sharp changes in depth along the crack profile. The principal limitation on accuracy is the change in pulse shape, which complicates identification of corresponding points in the transmitted and received waveforms. Tests carried out under compressive load demonstrated the continued accuracy of this technique even for tight cracks, whose ability to transmit ultrasound is a serious problem for both amplitude techniques and for the surface wave methods discussed below. This P-wave technique has been developed at Harwell to the point where visual estimation of transit time has been replaced by an electronic measurement system. By extending this electronic system to convert time measurement to crack depth, an automatic accurate crack depth meter could become available in the near future. In addition, different probe arrangements suitable for a wide variety of specimen geometries are being investigated.²⁸

One particularly simple method is to mount a single probe on the face opposite the crack, and to use time measurement to determine distance from the crack tip to the opposite face of the specimen. This approach was used by both Hunt²⁹ and Winters³⁰ to measure the depth of fatigue cracks opening on the inside of large gun barrels. The observed weak signals were attributed to reflections by facets near the crack tip; some cracks tending to be normal to the surface were missed by this method.²⁹ The technique was reliable only for cracks deeper than 2–4 mm. Both authors reported a systematic depth indication 0–1 mm below the true values. Silk and Lidington²⁸ also found considerable variations in the success of this technique when applied to fatigue cracks. They discussed in an oversimplified way the relative contributions to the signal from diffraction, refraction and scattering by micro-defects near the crack tip. A more detailed theoretical study of these mechanisms including the effect of mode conversion is needed to establish when this single probe timing method is reliable. This study would be doubly valuable if carried out in conjunction with photoelastic or Schlieren visualization experiments.

The use of the slower S-waves rather than P-waves increases the accuracy in converting from time delay to crack depth by a factor of about two. This advantage is not easily realized in practice with conventional S-wave probes, due to difficulty in identifying the relevant S-wave echoes among interfering signals^{27,28}. However, using a specially constructed short pulse S-wave probe arranged as in Fig. 6, Lloyd³¹ measured the depth of artificial slits 0.75–4.5 mm deep to ± 0.25 mm. His method is based on the theory of Freedman³², which shows that the return signal consists predominantly of pulses scattered from discontinuities, in this case the base and the tip of the slit. Further work directed towards exploiting the lower speed of S-waves for other probe configurations could prove profitable, particularly if more attention is paid to probe design to reduce spurious signals.

3.2 Surface Wave Timing Methods

Several authors have recently investigated the use of surface waves for crack depth measurement. Because they follow the crack profile, surface waves measure the *length* L along the crack face to its tip, rather than the more useful crack *depth* of the tip below the specimen surface (Fig. 7a); however, as we shall see later, more complicated experiments can eliminate this restriction. Also, the greater ability of these waves to penetrate small gaps often requires tight cracks, or cracks with solid or liquid filled gaps, to be opened by suitable loading of the specimen if depth measurement is to be achieved.

When a surface wave reaches a discontinuity such as a crack opening or tip, part of the energy will be radiated as P or S waves into the body of the specimen and part will be reflected

back as a surface wave, leaving the remainder to bend around the corner and continue as a surface wave. Cook³³ found the crack length L by measuring the time taken for the surface wave to pass around the crack between two transducers (Fig. 7b). This method was later found to be accurate for most fatigue cracks having L above 2 mm, provided the transmitted signal could be unequivocally identified³⁴. Unfortunately, attenuation of the surface wave caused by the crack morphology and the roughness of the surface finish prevented this method being accurate in some cases, and perhaps more importantly, it was not possible to know beforehand which cracks would be unsuitable. Hall³⁵ further clarified this technique by using photoelastic visualization of the interaction between a surface wave and notches in glass specimens. He demonstrated that three main pulses are expected at the receiver—the R-wave transmitted around the crack, a mode converted S-wave propagating from the tip over a range of directions including that towards the receiver, as well as a diffracted S-wave caused by an unwanted bulk wave produced at the transmitter (Fig. 7c). This insight facilitated the measurement of 9 mm deep fatigue cracks in steel using specially designed 4.2 MHz Rayleigh wave probes. Notches down to about 1 mm were indicated by broadening of the received pulse, though quantitative depth measurement by simple timing only becomes possible when the three main signals are resolved.

Hudgell *et al.*³⁴ introduced an alternative method suitable for parallel-sided specimens (Fig. 8), which uses only a single probe. This method is less accurate than that originated by Cook³³, but more reliable because it more consistently provides an identifiable signal. Total transit time is measured for that part of the surface wave which is converted to an S-wave at the tip, reflected from the opposite face of the flat specimen, then re-converted to a surface wave due to glancing incidence at the tip, and finally travels back to the probe. Because of the relatively small difference between R and S wave velocities, this method required measurement to ± 10 ns by time interval averaging to estimate fatigue crack edge profiles only to within about 1 mm. An inherently more accurate single probe technique measures the time lapse between R-wave reflections from the crack opening and from the crack tip. Lidington and Silk³⁶ used this approach to measure the depth of an artificial slit up to 30 mm deep to an accuracy of ± 0.2 mm. They were not able to deal with slits below about 4 mm, since for smaller depths the tip reflection was not resolved from the moderately short pulse from the slit opening. For a fatigue crack profile in steel, their accuracy in measuring L dropped to ± 0.8 mm, possibly due to a large inclusion concentration giving greater background intensity in the signal. Some spuriously high and low readings were found for this real crack, probably caused by changes in the crack angle and by regions of cracking parallel to the plate surface.

Silk²⁴ proposed several methods aimed at finding depth rather than length for a real crack. The most interesting of these first measures the times of flight between two transducers for the surface wave propagating around the crack, and for the mode converted S-wave originating at the tip (Fig. 9). Next, the roles of transmitting and receiving probes are reversed, and the measurements repeated. With these four readings, the time delay involving surface waves can be eliminated altogether, leaving the algebraic equivalent of the bulk S-wave timing method of Lloyd³¹. Silk used this method to find the depth rather than L for conveniently deep (22–30 mm) fatigue cracks to ± 0.5 mm.

The surface wave techniques described here have generally not been able to measure such small fatigue cracks as have the more successful of the bulk wave methods considered above, nor have they usually been so accurate, reliable, or versatile. Nevertheless, the approach is at a comparatively early stage of development, and as Silk²⁴ pointed out, may not yet have reached its full potential, particularly if viewed in the light of the more sophisticated treatment of the received pulses discussed in the following section.

4. ULTRASONIC SPECTROSCOPIC ANALYSIS

The transit time techniques considered so far rely on one or more pulses being identified at the receiver without any need for processing the total signal. One approach to extending these methods to smaller cracks and to mapping the morphology of the crack face is to pursue further analysis of the signal, either in the time domain or in the frequency domain, that is, to adapt the development of ultrasonic spectroscopy^{37,38} to signals from surface flaws. Work in this field has to date been mainly directed towards the study of internal defects. We shall briefly discuss this work, as it will help guide the development of the spectroscopic study of surface defects.

Because of the difficulty in developing the theoretical analysis, Gericke³⁷ and Wüstenberg and Mundry³⁹ suggested empirically forming an atlas of signatures for reflections from different types of internal flaws, to which one could refer to interpret the spectral traces obtained from unknown defects. However, ultrasonic spectroscopy has developed along rather more manageable lines through experimental and theoretical studies of the spectral traces from simply shaped objects. This work includes a method for the determination of the size of arbitrarily oriented flaws of two-dimensional (crack-like) geometry^{40,41}, and studies of cylindrical inclusions⁴²⁻⁴⁴ and of spheroidal cavities¹⁷ in elastic solids.

The same general approach described above for internal defects was adopted for surface flaws by Morgan⁴⁵. He applied spectroscopic analysis techniques to the study of surface wave reflections from a slot milled in aluminium. The reflections from this slot using a broad-band (0.5–10 MHz) interdigital transducer were as in Fig. 10a. Each corner in the slot whose shape is shown in Fig. 10b acts as a scattering centre. He introduced two methods—the time reconstitution method and the cepstral method—which allow later signals to be resolved from each other, provided the signal from the first scatterer can be separated. The time reconstitution method requires that both amplitude and phase of the reflected signal be retained for analysis. For this method, Morgan wrote the impulse response function for the surface crack in terms of reflection and transmission coefficients for a set of scatterers, which in this case were the corners in the slot. He assumed no change in pulse shape upon reflection, thereby neglecting dispersion. Fig. 10c shows the experimentally reconstituted time signal for the artificial slot and illustrates the correlations with the five scattering centres. The cepstral method, which does not require the phase of the reflected signal, gave results almost identical to Fig. 10c for the artificial slot. For this alternative method analogue spectrum analysers are applicable, instead of the digital processing required to obtain phase information for the time reconstitution approach.

In defining his original impulse response function, Morgan did not consider the effect of internal cycles between scatterers in the series. To improve the correlation between signal and slit morphology, these contributions to the signal should be evaluated and compared with the errors inherent in the computational procedures. The future development of his methods also depends on their extension to the morphologies of real surface cracks.

The energy carried by a surface wave is spread over a finite depth below the surface, governed by the wavelength. Therefore the time taken to pass around a crack whose depth is of the order of the wavelength is frequency dependent. Silk²⁴ suggested developing a technique for crack depth measurement based on this dependence which, while being less accurate than conventional transit time measurements, would be largely independent of the angle of the crack. We believe that a study of this frequency dependence may prove most valuable in the analysis of broadened pulses received in the interrogation of shallow cracks, such as have been reported by Hall³⁵. In any case, a more rigorous treatment of the frequency dependence than has been given to date is required.

5. DISCUSSION

From the techniques considered in this review, bulk wave transit time measurements appear to hold the main hope for the near future to provide simple and reliable quantitative crack depth measurement. Surface wave timing methods are also promising, though they are perhaps at a slightly earlier stage of development. Further fundamental scattering studies such as those described will be valuable in providing the necessary general understanding of the basic processes involved, particularly if applied to the scattering in the region of the crack tip.

Not only greater accuracy and reliability of depth measurement are desirable, but also the ability to measure smaller cracks; for example, cracks 0.5 mm deep are often critical in high strength steels in aircraft components. Research in ultrasonic spectroscopic analysis, possibly along the lines suggested, should contribute to the study of small cracks. For some specimen geometries, another approach which may be developed to provide quantitative measurement is the use of guided ultrasonic waves. These waves have been used to detect cracks down to 0.05 mm in thin tubes⁴⁶.

The ultrasonic probes used are another area for development. Greater accuracy and sensitivity in measuring the depth of the profile of small cracks may be possible by the use of

focused probes⁴⁷, and particularly by the use of single pulse generation⁴⁸⁻⁵⁰. Again, improved probe design may allow exploitation of the inherent advantage of shear waves over pressure waves for timing techniques. Finally, we should mention that only single cracks have been studied to date; multi-branched cracks, and close clusters of cracks, are subjects for future study.

REFERENCES

1. Thompson, R. B., and Evans, A. G. Goals and objectives of quantitative ultrasonics, *IEEE Trans. Sonics and Ultrasonics* SU-23 (1976) 292.
2. Krautkrämer, J., and Krautkrämer, H. *Ultrasonic Testing of Materials*, Springer-Verlag (1969).
3. Hitt, W. C. Progress in the field of non-destructive testing through the use of ultrasonics. *Proc. ASTM Symposium* (1952) 53.
4. Hislop, J. D. Flaw size evaluation in immersed ultrasonic testing. *Non-destructive Testing* 2 (1969) 183.
5. Krautkrämer, J., Determination of the size of defects by the ultrasonic impulse method, *Brit. J. Appl. Phys.* 10 (1959) 240.
6. Birchak, J. R., and Gardner, C. G. Comparative ultrasonic response of machined slots and fatigue cracks in 7075 aluminium, *Mat. Evaluation* 34 (1976) 275.
7. Corbly, D. M., Packman, P. F., and Pearson, H. S. Accuracy and precision of ultrasonic shear wave flaw measurements as a function of stress on the flaw, *Mat. Evaluation* 30 (1970) 103.
8. Yee, B. G. W., Couchman, J. C., Hagemayer, J. W., and Chang, F. H. Stress and the ultrasonic detection of fatigue cracks in engineering metals, *Non-destructive Testing* 7 (1974) 245.
9. Werneyer, R., and Schlenger, U. The reflection of ultrasonic waves by surface cracks and notch-shaped reference defects—introduction and model conception, *Materialprüfung* 13 (1971) 213.
10. Lidington, B. H., Saunderson, D. H., and Silk, M. G. Interference effects in the reflection of ultrasound from shallow slits, *Non-destructive Testing* 8 (1975) 185.
11. Babrovsky, V. M., Marsh, D. M., and Slater, E. A. Schlieren and computer studies of the interaction of ultrasound with defects, *Non-destructive Testing* 6 (1973) 200.
12. Babrovsky, V. M., and Marsh, D. M. A Schlieren study of ultrasonic pulse propagation and reflection, T.I. Research Labs Report 307 (1971).
13. Kraut, E. A. Review of theories of scattering of elastic waves by cracks, *IEEE Trans. Sonics and Ultrasonics* SU-23 (1976) 162.
14. Gubernatis, J. F., Domany, E., Huberman, M., and Krumhansl, J. A. Theory of the scattering of ultrasound by flaws, *Ultrasonics Symposium Proceedings*, IEEE New York (1975) 107.
15. Gubernatis, J. E., Domany, E., Krumhansl, J. A., and Huberman, M. The Born approximation in the theory of the scattering of elastic waves by flaws. *J. Appl. Phys.* 48 (1977) 2812.
16. Tittmann, B. R. Measurements of scattering of ultrasound by ellipsoidal cavities. *Interdisciplinary Program for Quantitative Flaw Definition Special Report*, 2nd Year Effort, Rockwell (1976) 123.
17. Adler, L., and Lewis, D. K. Scattering of a broadband ultrasonic pulse by discontinuities, *IEEE Trans. Sonics and Ultrasonics* SU-23 (1976) 351.
18. Bennett, S. B. Scattering of a plane elastic wave from objects near an interface, *J. Appl. Mech.* 39 (1972) 1019.
19. Babrovsky, V. M., Slater, E. A., and Marsh, D. M. The response of ultrasound to defects. *Ultrasonics International 1975 Conference Proceedings* (1975) 46.

20. Böttcher, B., Schulz, E., and Wüstenberg, H. A new method of crack determination in ultrasonic materials testing. Proc. 7th International Conference on Non-destructive Testing, Warsaw (1973).
21. Silk, M. G., and Lidington, B. H. The potential of scattered or diffracted ultrasound in the determination of crack depths. *Non-destructive Testing* **8** (1975) 146.
22. Reinhardt, H. W., and Dally, J. W. Some characteristics of Rayleigh wave interaction with surface flaws. *Materials Evaluation* **30** (1970) 213.
23. Ho, C. L., Marcus, H. L., and Buck, O. Ultrasonic surface wave detection techniques in fracture mechanics. *Experimental Mechanics* **14** (1974) 42.
24. Silk, M. G. The determination of crack penetration using ultrasonic surface waves. *NDT International* **9** (1976) 290.
25. Di Giacomo, G., Crisci, J. R., and Goldspiel, S. An ultrasonic method for measuring crack depth in structural weldments. *Materials Evaluation* **30** (1970) 189.
26. Silk, M. G., and Lidington, B. H. Defect sizing using an ultrasonic time delay approach. *Brit. J. Non-destructive Testing* **17** (1975) 33.
27. Lidington, B. H., Silk, M. G., Montgomery, P., and Hammond, G. Ultrasonic measurements of the depth of fatigue cracks. *Brit. J. Non-destructive Testing* **18** (1976) 165.
28. Silk, M. G., and Lidington, B. H. An evaluation of single probe bulk-wave time-delay techniques in sizing cracks in steel. *NDT International* **10** (1977) 129.
29. Hunt, C. A. Non-destructive measurement of cracks in gun barrels. RARDE Technical Report 20/75 (1975).
30. Winters, D. C. End-on crack measurement, 1975 Ultrasonic Symposium Proceedings, IEEE Cat # 75, CHO 994-4SU (1975) 572.
31. Lloyd, E. A. An ultrasonic short-pulse shear wave method for measuring the depth of surface breaking cracks. *Brit. J. Non-destructive Testing* **17** (1975) 172.
32. Freedman, A. A mechanism of acoustic echo formation. *Acustica* **12** (1962) 10.
33. Cook, D. Crack depth measurement with surface waves. Proc. Brit. Acoustical Soc. Spring Meeting, Loughborough (1972) 72U19.
34. Hudgell, R. J., Morgan, L. L., and Lumb, R. F. Non-destructive measurement of the depth of surface-breaking cracks using ultrasonic Rayleigh waves, *Brit. J. Non-destructive Testing* **16** (1974) 144.
35. Hall, K. G. Crack depth measurement in rail steel by Rayleigh waves aided by photoelastic visualization. *Non-destructive Testing* **9** (1976) 121.
36. Lidington, B. H., and Silk, M. G. Crack depth measurements using a single surface wave probe. *Brit. J. Non-destructive Testing* **17** (1975) 165.
37. Gericke, O. R. Ultrasonic spectroscopy, Ch. 2 in *Research Techniques in Non-destructive Testing*. Ed. R. S. Sharpe Academic Press London and N.Y. (1970).
38. Brown, A. Materials testing by ultrasonic spectroscopy. *Ultrasonics* **11** (1973) 202.
39. Wüstenberg, H., and Mundry, E. Consideration of the ultrasonic testing method as an information transfer system. *Brit. J. Non-destructive Testing* **15** (1973) 36.
40. Adler, L., and Whaley, H. L. Interference effect in a multifrequency ultrasonic pulse echo and its application to flaw characterization. *J. Acoust. Soc. Am.* **51** (1972) 881.
41. Adler, L., Cook, K. V., Whaley, H. L., and McClung, R. W. Flaw size measurement in a weld sample by ultrasonic frequency analysis. *Materials Evaluation* **35** (1977) 44.
42. Sachse, W. Ultrasonic spectroscopy of a fluid-filled cavity in an elastic solid. *J. Acoust. Soc. Am.* **56** (1974) 891.
43. Bifulco, F., and Sachse, W. Ultrasonic pulse spectroscopy of a solid inclusion in an elastic solid. *Ultrasonics* **13** (1975) 113.

44. Sachse, W. Scattering of ultrasonic pulses from cylindrical inclusions in elastic solids. *Proc. ARPA/AFML Review of Quantitative NDE*. AFML-TR-75-212 (1976) 147.
45. Morgan, L. L. The spectroscopic determination of surface topography using acoustic surface waves. *Acustica* **30** (1974) 222.
46. Mohr, W., and Höller, P. On inspection of thin-walled tubes for transverse and longitudinal flaws by guided ultrasonic waves. *IEEE Trans. Sonics and Ultrasonics* SU-23 (1976) 369.
47. McElroy, J. T. Focused ultrasonic beams. *Int. J. Non-destructive Testing* **3** (1971) 27.
48. Dixon, N. D., and Davis, T. J. A new triangular acoustic pulse—its generation and unique properties for NDT applications. Battelle Northwest Labs. Report BNWL-1256, VC-37, Instruments (1971).
49. Korolev, M. V. New aperiodic ultrasonic piezoelectric transducers. *Sov. J. Non-destructive Testing* **12** (1976) 296.
50. Kazhis, R-I. Y., Lukoshevichyus, A. I., and Sayouskas, S. I. Unipolar narrow ultrasonic pulse generator. *Sov. J. Non-destructive Testing* **9** (1973) 628.

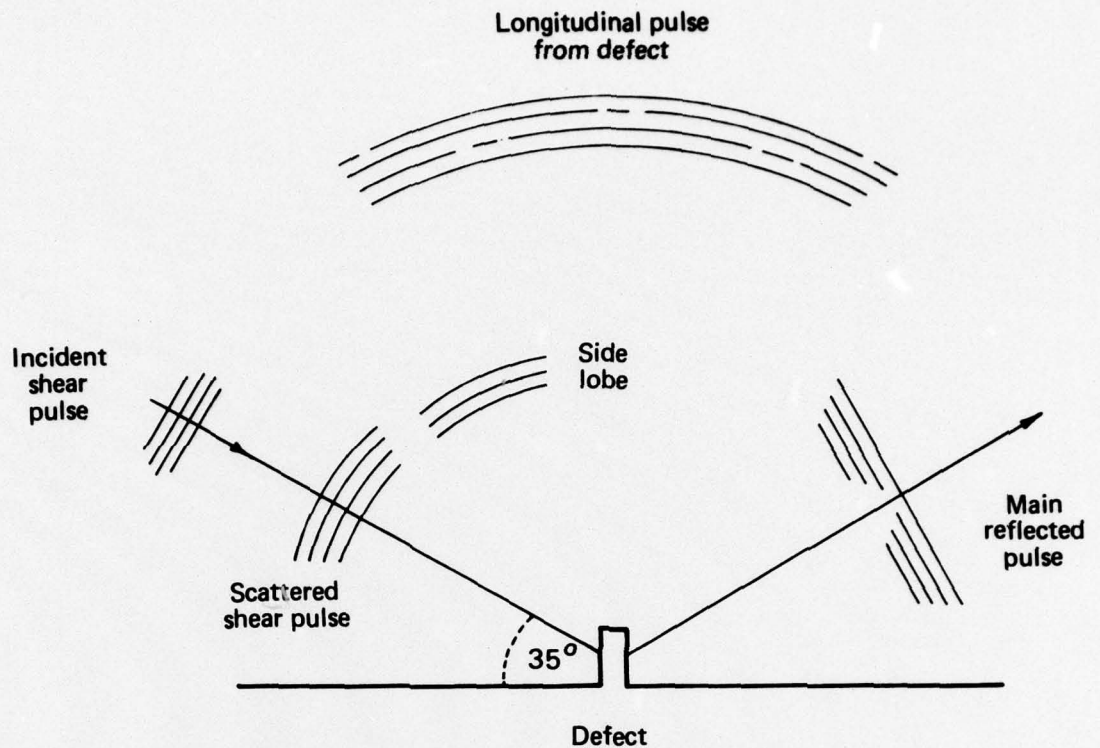


FIG. 1 SKETCH OF A CROSS-SECTION THROUGH THE FIELD PRODUCED BY A 2MHz SHEAR WAVE PULSE INCIDENT AT 35° ON A SLIT TWO WAVELENGTHS DEEP IN STEEL¹².

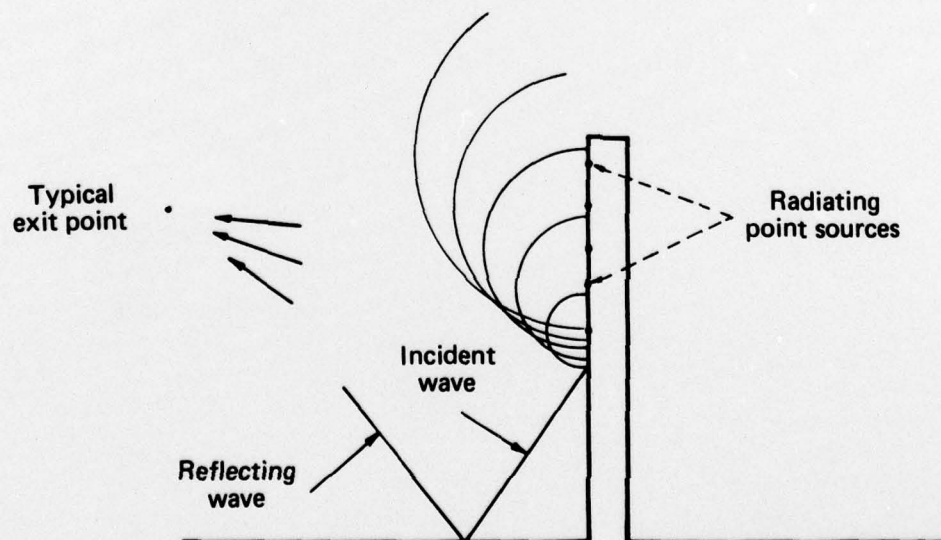


FIG. 2 ILLUSTRATING THE MODEL OF BABOROVSKY ET AL¹⁹; FOR CLARITY ONLY RADIATED WAVES OF ONE MODE CAUSED BY DIRECT ILLUMINATION ARE SHOWN.

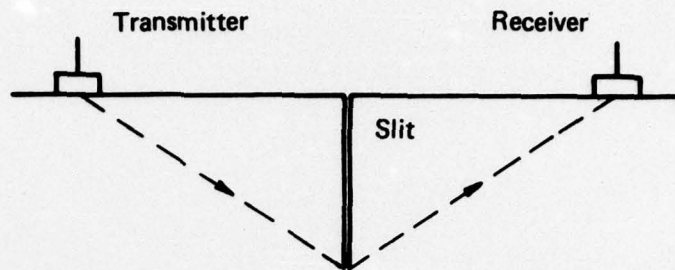


FIG. 3 THE TWO PROBE CONFIGURATION USED BY BOTTCHER ET AL²⁰.

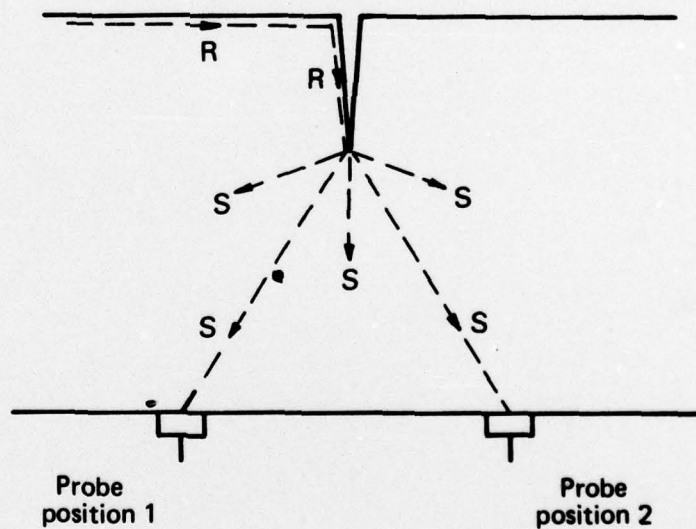


Fig. 4

FIG. 4
DEPTH MEASUREMENT BY DETECTING S-WAVES PRODUCED BY MODE CONVERSION OF R WAVES AT THE TIP USING AN S-WAVE DETECTOR OF KNOWN ANGLE θ .

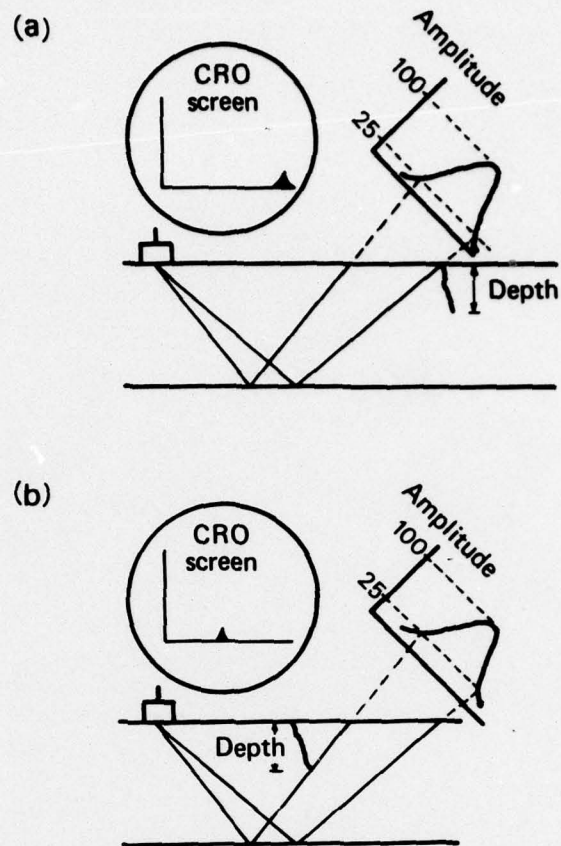


FIG. 5 THE TECHNIQUE DEVELOPED BY DI GIACOMO ET AL²⁵; (A) AND (B) SHOW THE TWO POSITIONS AT WHICH READINGS WERE TAKEN.

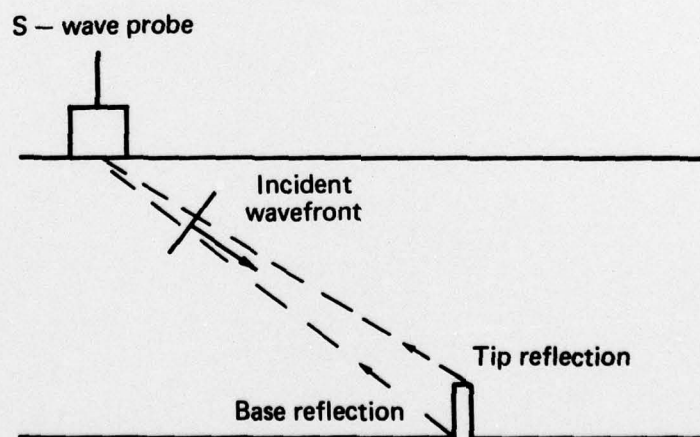


FIG. 6 THE S-WAVE METHOD OF LLOYD³¹; THE BASE REFLECTION IS COINCIDENT WITH THE SPECULAR REFLECTION.

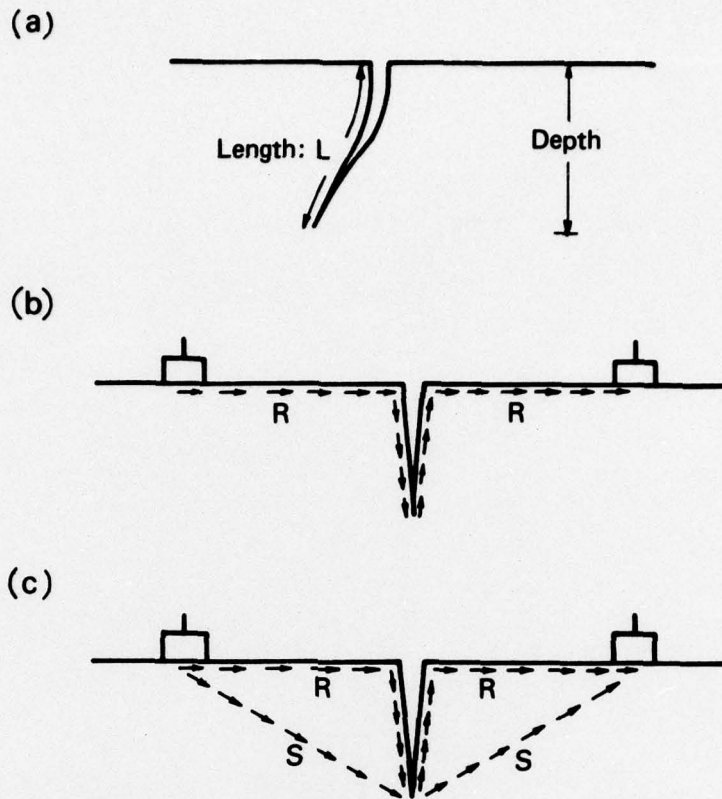


FIG. 7 CRACK LENGTH MEASUREMENT USING SURFACE WAVES.

- (a) Distinction between crack depth and the crack length L .
- (b) Crack length measured by the surface wave propagating around the crack.
- (c) The three main pulses expected at the receiver. Note that P, S and both reflected and transmitted R-Waves are in general all produced at each discontinuity.

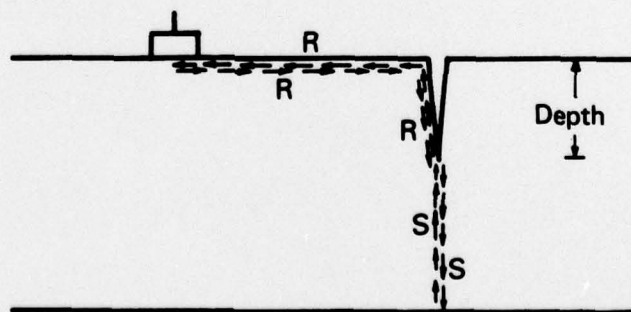


FIG. 8 CRACK LENGTH MEASUREMENT USING THE DIFFERENCE BETWEEN SPEEDS FOR R AND S WAVES.

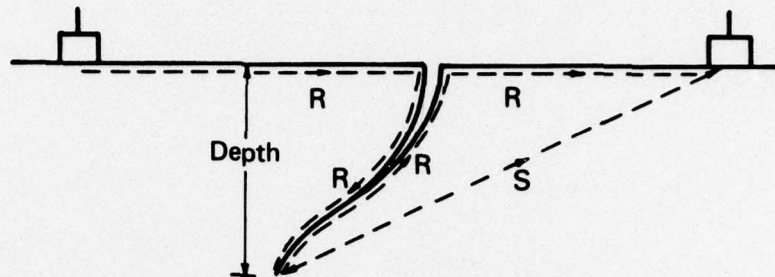


FIG. 9 ELIMINATION OF R-WAVE TRANSIT TIMES TO FIND CRACK DEPTH²⁴.

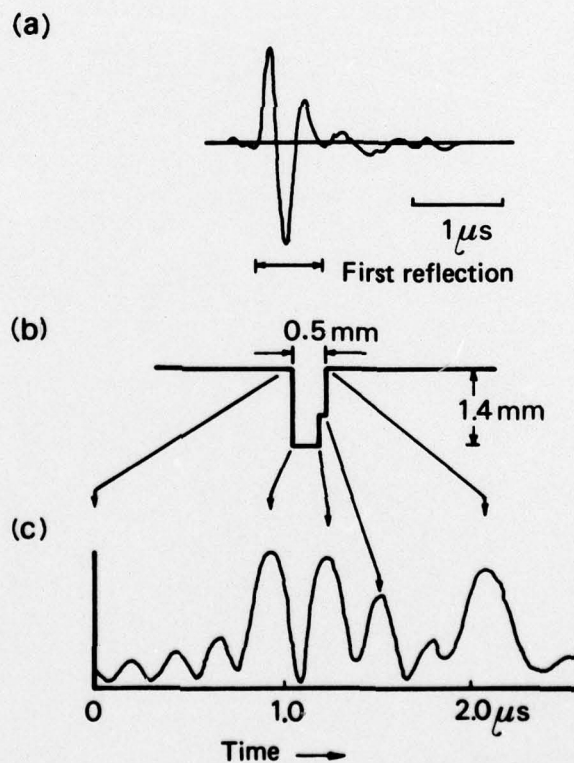


FIG. 10 THE SPECTROSCOPIC ANALYSIS CARRIED OUT FOR SURFACE WAVES BY MORGAN⁴⁵.

- (a) The original reflected signal.
- (b) The geometry of the slot.
- (c) The experimentally reconstituted time signal.

DISTRIBUTION

Copy No.

AUSTRALIA

DEPARTMENT OF DEFENCE

Central Office

Chief Defence Scientist	1
Executive Controller, ADSS	2
Superintendent, Defence Science Administration	3
Defence Library	4
JIO	5
Assistant Secretary, DISB	6-21

Aeronautical Research Laboratories

Chief Superintendent	22
Superintendent, Materials Division	23
Divisional File, Materials Division	24
Authors: P. A. Doyle	25
C. M. Scala	26
Library	27

RAN Research Laboratory

Library	28
---------	----

Air Force Office

Air Force Scientific Adviser	29
SENGSO, Support Command H.Q.	30

Materials Research Laboratories

Library	31
---------	----

Weapons Research Establishment

Library	32
---------	----

STATUTORY, STATE AUTHORITIES AND INDUSTRY

Australian Atomic Energy Commission (Director)	33
C.S.I.R.O. Central Library	34
Qantas, Library	35
Trans-Australia Airlines, Library	36
Ansett Airlines of Australia, Library	37
BHP Melbourne Research Laboratories	38

UNIVERSITIES AND COLLEGES

Melbourne	Engineering Library	39
Monash	Library	40
	Professor I. J. Polmear	41
New England	Library	42
New South Wales	Physical Sciences Library	43

CANADA

NRC, National Aeronautics Establishment, Library 44

FRANCE

AGARD, Library 45

ONERA, Library 46

GERMANY

ZLDI 47

INDIA

CAARC Co-ordinator Materials 48

JAPAN

National Aerospace Laboratory, Library 49

NETHERLANDS

Central Organization for Applied Science Research in the Netherlands TNO, Library 50-51

National Aerospace Laboratory (NLR) Library 52

NEW ZEALAND

Air Department, RNZAF, Aero. Documents Section 53

Transport Ministry, Civil Aviation Division Library 54

UNITED KINGDOM

Australian Defence Science and Technical Representative 55

CAARC NPL (Secretary) 56

Royal Aircraft Establishment Library, Farnborough 57

Royal Armament Research and Development Establishment, Library 58

Admiralty Materials Laboratories (Dr R. G. Watson) 59

British Library, Science Reference Library 60

British Non-Ferrous Metals Association 61

Central Electricity Generating Board 62

Metals Abstract (Editor) 63

Welding Institute, Library 64

Non-Destructive Testing Centre, AERE, Harwell (Director) 65

Universities and Colleges

City University, London Library 66

Cranfield Institute of Technology Library 67

Imperial College The Head 68

UNITED STATES OF AMERICA

Counsellor, Defence Science 69

NASA Scientific and Technical Information Facility 70

Applied Mechanics Reviews 71

The Chemical Abstracts Service 72

Battelle Memorial Institute, Library 73

Rockwell International (Director) 74

Air Force Laboratories, Dayton, Ohio (Director) 75

Universities and Colleges
Cornell (Ithaca)

Library

76

SPARES

77-86